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Obtaining Stress-% Compression Diagrams of Foamed Plastics at High Rates of Compression

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A test machine is described which will load specimens in compression at rates as high as 30 ips or 6000 %/sec for a ½-in-thick sample. The rate of compression and the shape of the % compression-time curve is readily varied. The stress-% compression diagram associated with any given % compression-time curve is plotted directly. An impact method which has been used to obtain stress-% compression diagrams with compression rates as high as 200,000 %/sec is discussed.

Applicable to foamed plastics

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Obtaining Stress-% Compression Diagrams of Foamed Plastics at High Rates of Compression

The widespread use of foamed plastics as cushioning and packaging material has made the knowledge of their dynamic properties imperative. One method of understanding how the rate of compressive loading affects behavior is through the stress-% compression diagram. Stress-% compression curves determined from tests using universal testing machines may be misleading because of the low rate of compression used during the test as compared to that encountered in cushioning problems. Several test devices[1] have been proposed and used to evaluate material properties at high rates. However, in most of these devices the rate of straining is not as great as in certain cushioning applications, or it has been impossible to control the shape of the strain-time curve so as to duplicate some expected type of loading.

The machine described in this paper permits the sample of interest to be loaded in compression with almost any desired strain-time curve, with a wide variety of shape factors,[2] and over a wide temperature range. The stress-strain diagram associated with these conditions is plotted directly. The impact technique discussed in this paper to study dynamic properties is used for higher rates of compression than possible with the machine, and has the advantage that the conditions under which properties are evaluated can easily be made to duplicate the conditions that will exist when the material is used for cushioning purposes under known impact conditions.

DESCRIPTION OF THE MACHINE

The basic machine, called the "variable rate machine," is shown in Fig.1. The Vicker's double

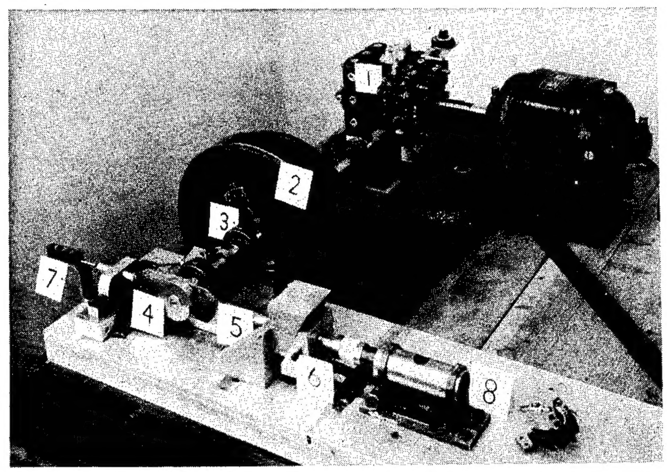

Fig. 1 Variable-rate testing machine

power unit (1), Fig.1, makes it possible to vary the angular velocity of the flywheel (2) from zero to 1000 rpm. When the flywheel has reached any desired angular velocity the spring-loaded trigger in the clutch (3) can be released so that it engages the flywheel. The clutch shaft drives the compression cam (4) which compresses the specimen through the push rod (5). The time required to compress the specimen depends upon the angular velocity of the flywheel; the shape of the compression-time curve depends upon the lift curve of the cam being used.

As an example, using a cam with a constant-velocity lift of 0.6 in. in 120 deg of rotation and with the flywheel turning at 1000 rpm, a 1-in-thick specimen will be compressed at constant rate by 60 per cent in 0.02 sec; i.e.,

$$\frac{1\ \text{min}}{1000\ \text{rev}} \times \frac{120^\circ\ \text{of lift}}{360^\circ/\text{rev}} \times \frac{60\ \text{sec}}{1\ \text{min}} = 0.02\ \text{sec}$$

This test will be carried out at a constant compression rate of 3000%/sec to 60% compression. Using this same cam, the rate of compression may be varied by varying the speed of the flywheel. Other cams are used to obtain different amounts of compression and/or different shapes of compression-time curves. Within limits, any shape

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1 "An Apparatus for the Determination of Stress-Strain Properties at High Rates of Strain," by R.J. MacDonald and R. L. Carlson, Proc. SESA, vol. 14, no. 1, 1956, pp. 163-170.

"A High-Speed Tension Testing Machine," by S. Strella, H. Sigler, M. Chmura, and B. Holman, ASTM Bul. no. 228, Feb., 1958.

2 The shape factor of a compression specimen is defined as the area of one of the faces on which the load is applied divided by the total free area of the specimen during compression.

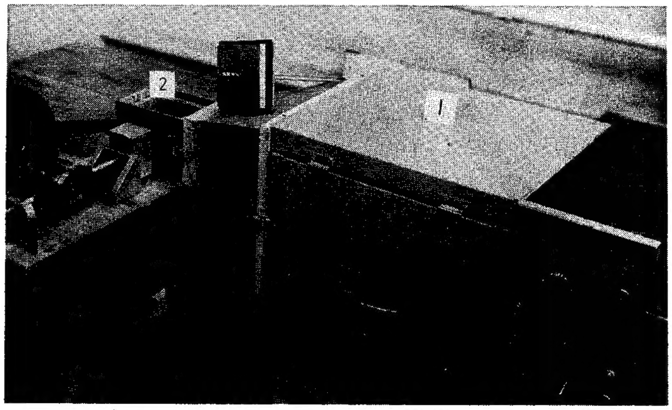


Fig. 2 Temperature chamber

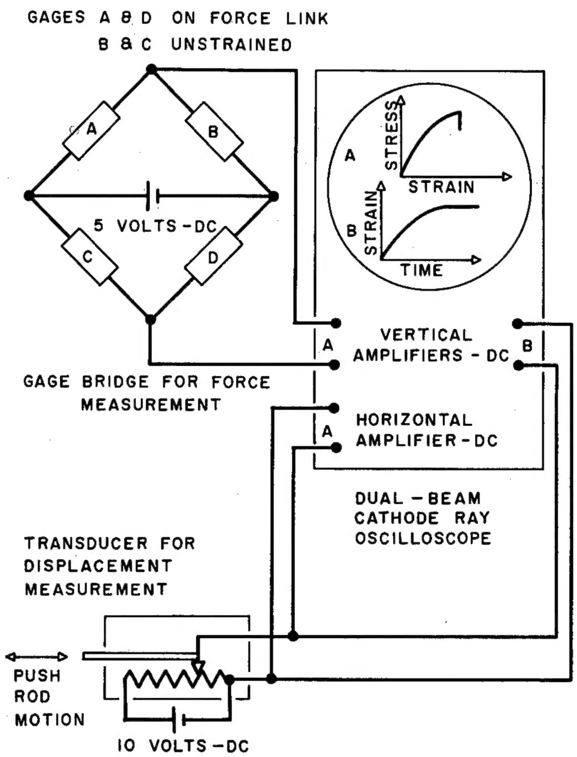


Fig. 3 Simplified circuit diagram

of % compression-time curve may be obtained by designing lift cams with the desired profile. Considerable use has been made of a cam having a constantly decreasing rate of compression.

All of the cams in use have a dwell portion (no lift) before and after the lift period. The initial dwell period allows most of the vibrations caused by engagement of the clutch and flywheel to subside before the actual compression of the specimen begins. The dwell portion of the cam following the lift period holds the specimen at maximum compression for a brief period following lift. While the specimen is held at maximum compression by the cam, the spring-loaded wedge

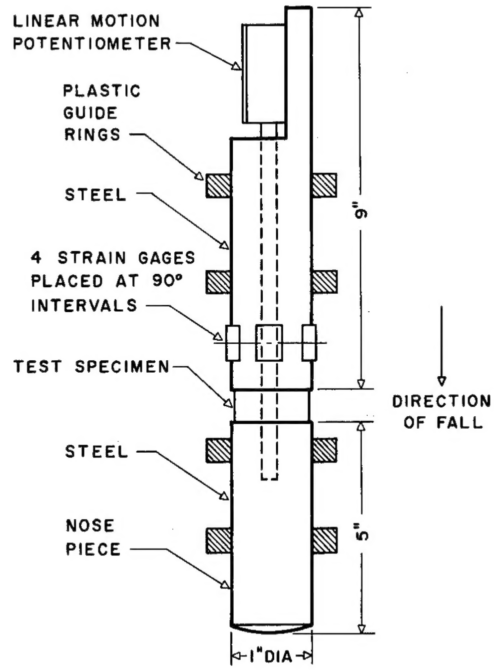


Fig. 4 Impact test vehicle

(6) engages. This wedge holds the specimen at maximum compression until it is manually released. This feature permits a study of stress relaxation which occurs in the sample during the constant-strain period.

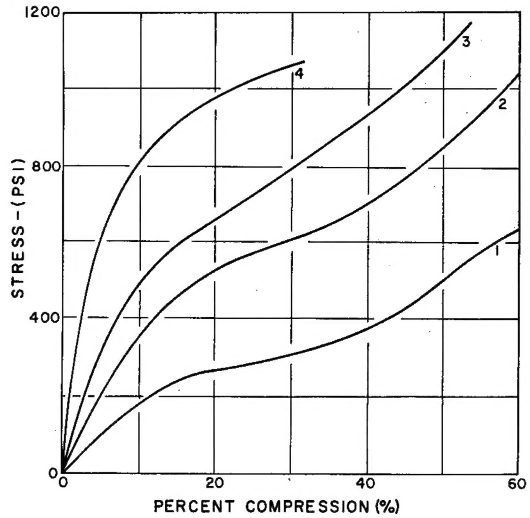
The amount of specimen compression is measured by means of an electric displacement gage[3] (7) attached to the push rod. Use of the push rod motion as sample compression assumes that (a) the change in length of the push rod when loaded is negligible, and (b) one surface of the sample remains fixed. Both of these assumptions were found to be justified for maximum loads of 1000 lb or less.

The amount of force required to compress the specimen is measured by means of the calibrated force link (8). This link consists of a brass plate, 1/2 in. in width, with an SR-4 strain gage[4] mounted on each side. Links of various thicknesses are used so as to give maximum sensitivity. As an example - when the maximum load is expected to be 1000 lb a link 0.187 in. thick is used; when the maximum load is expected to be 100 lb a link 0.020 in. thick is used.

To account for the possible effect of specimen size on the stress-% compression diagrams, the concept of shape factor is utilized. The

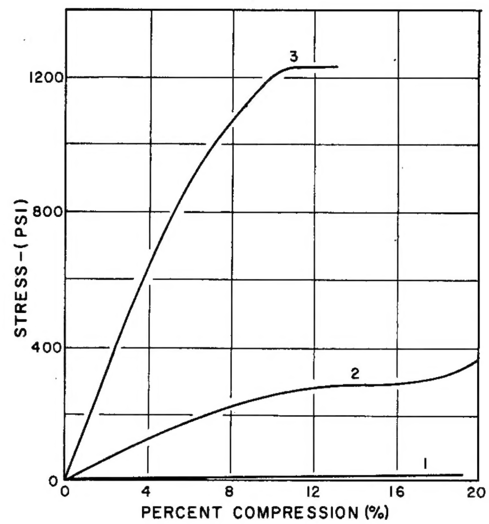
[3] Linear motion potentiometer, Model 108 Bourns Laboratories, Inc.

[4] Type A-12 500 ohms resistance. Gage factor 2.0, Baldwin-Lima-Hamilton Corporation.



CURVE	MAXIMUM COMPRESSION RATE - (% /SEC)	TEMPERATURE (°F)
1	47.4	77
2	2180	77
3	3220	73
4	42600	75

Fig. 5 Stress-% compression curves for a foamed plastic at several compression rates



CURVE	MAXIMUM COMPRESSION RATE - (% /SEC)	TEMPERATURE (°F)
1	5.8	138
2	5.2	80
3	5.1	-17

Fig. 6 Stress-% compression curves for a foamed plastic at several temperatures

specimen may be tested as shown in Fig.1, in which case the shape factor is fixed by the dimensions of the specimen; or the specimen may be tested with a sleeve enclosing the free area of the sample. In the latter case, with the specimen completely confined, the shape factor becomes infinite; i.e., zero free area. For a material with a Poisson's ratio of approximately zero (possible for foamed plastics) the stress-% compression curve will be independent of the shape factor.

Fig.2 shows the temperature chamber used to enclose the test specimen when results are desired for temperature either above or below room temperature. The main chamber (1) forces hot (or cold) air around the specimen in the box (2) until the desired equilibrium temperature is reached. Data have been obtained from -10 to +200 F.

Fig.3 indicates how the two transducers, displacement gage, and force link, are connected to the recording equipment. Since the oscilloscope used is a dual-beam unit, two plots are obtained simultaneously. The signal from the force link (which is proportional to specimen stress) is plotted on the vertical axis versus the output of the displacement gage (which is proportional to % compression) on the horizontal axis. This gives the desired stress-% compression diagram. Simultaneously, the same signal from the displacement gage is plotted on the vertical axis versus time on the horizontal axis. The time axis is obtained by using the internal sweep provision. This plot gives the % compression-time diagram for which the stress-% compression diagram applies. Since both traces are made simultaneously they are recorded on a single frame of an oscilloscope camera.

IMPACT METHOD

When the impact method is used the equipment for determining the stress-% compression diagram consists of the following items: (a) Drop tower for accelerating the vehicle which holds the sample to be tested. (b) A transducer for measuring the force transmitted by the sample and provision for displaying this transmitted-force signal as a function of time. (c) A transducer for measuring the compression of the sample and provision for displaying this compression signal as a function of time.

The test vehicle with the sample in place can be accelerated by gravity alone or by a combination of shock cords and gravity. The test vehicle is guided to the impact surface by means of the three taut wires.

A typical test vehicle is shown in Fig.4. In this case the foam-plastic sample to be tested is a right circular cylinder, approximately 1 in. diam and 1/2 in. thick. The sample may be compressed with no lateral constraint as shown here,

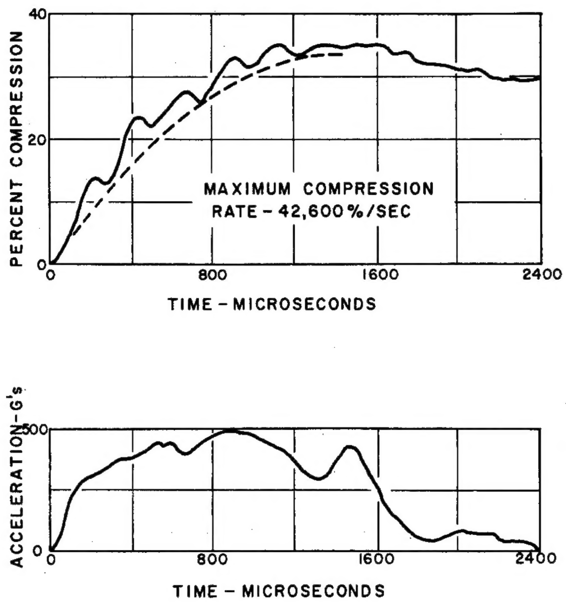


Fig. 7 Typical impact test data

or it may be enclosed in a metal sleeve to provide lateral constraint. During a test using the vehicle shown in Fig. 4, the signal from the linear motion potentiometer[5] is recorded as a function of time on one trace of a dual beam oscilloscope. The signal from the strain gages[6] is recorded as a function of time on the other trace of the same oscilloscope.

The signal from the linear-motion potentiometer is proportional to the sample compression, since the potentiometer case is fixed to the mass above the sample, and the potentiometer stem is fixed to the nose piece.

The signal from the strain gages is proportional to the force transmitted by the sample, which is the same as the force on the sample. This may be shown in the following manner:

At any time, t, the force acting at the point where the gages are attached, F_g, is equal to the mass of the bar above the gages, M_g, times the acceleration of the bar, A_b; i.e.,

$$F_g = M_g \times A_b \tag{1}$$

The force at the interface between the gaged bar and the sample, F_s, is

$$F_s = M_s \times A_b, \tag{2}$$

where M_s is the mass of the vehicle above the sample.

[5] Model 108, Bourns Laboratories, Inc.

[6] SR-4, Type A-14, Baldwin-Lima-Hamilton Corp.

Eliminating the acceleration of the bar from these equations, the force on the sample becomes

$$F_s = \frac{M_s}{M_g} \times F_g \tag{3}$$

The force at the gage point may be determined from the strain at this point, ϵ, the modulus of elasticity of the bar, E, and the area of the bar, A, by the relation

$$F_g = E \epsilon A. \tag{4}$$

The strain, ϵ, is determined from the magnitude of the signal from the strain gages at any time, t. Substituting (4) into (3), gives

$$F_s = \frac{M_s E \epsilon A}{M_g} \tag{5}$$

Using equation (5) the stress in the sample at any time, t, may be found, and the stress-% compression curve for those particular impact conditions plotted.

The linear-motion potentiometer used on the vehicle shown in Fig. 4 does not function satisfactorily when subjected to the high acceleration encountered when testing the more rigid foam plastics due to the high accelerations applied to it. Therefore, when these foams are tested, another means of measuring specimen compression is required. When a rigid impact surface (steel block) is used, the lower surface of the sample may be considered fixed immediately after impact occurs, and the compression of the sample may be obtained by finding the displacement of the upper sample surface. This can be accomplished by means of a double integration of the stress-time curve if the velocity at impact, V_i, is known:

$$A_b = \frac{F_s}{M_s} = \frac{s(t)A}{M_s} = \frac{dV_b}{dt}$$

where s(t) represents sample stress as a function of time.

V_b = velocity of bar

$$V_b(t) = \frac{A}{M_s} \int_{V_i}^{o} s(t)\, dt = \frac{dS_b}{dt},$$

where S_b = displacement of bar after impact.

$$S_b(t) = \frac{A}{M_s} \int_{V_i}^{o} \int_{o}^{s} s(t)\, dt$$

A point on the stress-% compression curve may

now be found by determining a stress from the s(t) curve at t_1, and the corresponding % compression from the sample thickness and S_b at t_1. Doing this for a series of points permits plotting the stress-% compression curve. For this method of obtaining the stress-% compression curve, the maximum rate of compression is limited only by the impact velocity possible for the tower.

If the mass above the sample is large, the rate of compression will be essentially constant to 50 or 60 per cent compression, as was the case for the variable-rate machine. If desired, the mass may be adjusted, using dimensional analysis, to give the same rate of compression curve as is anticipated in a particular cushioning application.

To obtain impact data at temperature extremes, the main chamber (item 1, Fig.2) of the equipment for the variable-rate machine was used, with a special adapter to fit the drop tower. For these tests, the specimen is placed on the anvil, brought to the desired temperature, and then the test is conducted. Data have been obtained from -60 to 165 F.

RESULTS

The two methods just described have been in use since July 1957, and data have been obtained on several types of foamed plastics and foamed metals. Results obtained from tests on a particular material[7] are included here to illustrate the capabilities of the variable-rate machine and the impact method. Fig.5 shows the effect of compression rate on the stress-% compression diagram. The data shown on this figure as curves 1, 2 and 3 were obtained from three tests. In each test the sample was confined (tested with infinite shape factor) and the rate of compression was decreasing at a constant rate. Fig.6 shows the results of tests conducted to establish the effect of temperature on the stress-% compression curve. The compression rate was essentially the same for all tests.

This same material was tested using the impact method. Fig.7 shows the data obtained from this test. Both of the curves shown appear simultaneously on the screen of the dual-beam, cathode-ray oscilloscope, and are photographed on a single frame of Polaroid film. The curves shown are traced from this photograph and appropriate scales added. The data presented in Fig.7 can also be plotted on stress-% compression coordinates. This has been done, and the result appears as curve 4 in Fig.5.

The oscillations in the compression time curve, Fig.7, indicate that the potentiometer is not functioning properly. For this test, the specimen compression should be determined by the double-integration method. The dotted % compression-time curve in Fig.7 was obtained by double integration of the stress-time curve.

Conclusions

The most obvious shortcoming of the variable-rate testing machine described is its rather low upper limit of compression rate. This upper limit is imposed by the excessive vibration and impact forces which result when tests are run with flywheel angular velocities of greater than 1000 rpm. Also, there is an upper limit on the force available for compressing the sample. This is imposed by the energy capacity of the flywheel.

The effect of rate of compression on the shape of the stress-% compression diagrams varies widely for various types of foam plastics which have been tested. The authors have made no attempt to explain the results on the basis of microscopic structure. Instead, with simple methods available for conducting tests at high compression rates, it has been possible to check the suitability of several materials for proposed cushioning applications.

[7] Stafoam No. X-112-1A, produced by the American Latex Corporation. Foamed to a density of 21 pcf.